Controller device with switchable characteristic

The present invention relates in general to a controller for an optical disc drive, for controlling certain parameters of an optical head of an optical disc drive.

As is commonly known, an optical storage disc comprises at least one track, either in the form of a continuous spiral or in the form of multiple concentric circles, of

5   storage space where data may be stored. Optical discs may be read-only type, where data is recorded during manufacture, which data can only be read by a user. The optical storage disc may also be a writable type, where data may be stored by a user. For writing data in the storage space of the optical storage disc, or for reading data from the disc, an optical disc drive comprises, on the one hand, means for receiving and rotating an optical disc, and on the

10   other hand an optical head for scanning the storage track with an optical beam, typically a laser beam. For instance, in reading data from a disc, a laser beam is generated and focussed on the track of the rotating disc. Reflected light is captured, and a data signal is retrieved from the reflected light beam. Since the technology of optical discs in general, the way in which data can be stored in an optical disc, and the way in which optical data can be read

15   from an optical disc, is commonly known, it is not necessary here to describe this technology in more detail.

For being able to fulfil its task, the optical head of an optical disc drive comprises movable parts. For instance, the optical head comprises a lens system with an objective lens which is displaceable in the Z-direction, i.e. the longitudinal direction of the

20   light beam, in order to focus the light beam exactly on the track of the optical disc. Further, the objective head is displaceable in the radial direction of the optical disc, in order to be able to follow the track of the optical disc. Even if the optical disc comprises multiple circular tracks, such track may in practice deviate from an exact circular shape, so that the optical head needs to be displaced in order to keep the focus spot of the laser beam exactly on track.

25   In the following, the present invention will be more specifically explained in relation to the focus control of the objective lens; however, it should be clear to a person skilled in the art that the same explanation, mutatis mutandis, is also valid for track control of the optical head.

For focus control, the objective lens is arranged displaceable in the Z-direction, and the disc drive comprises a controllable actuator operatively associated with the objective lens for displacing the objective lens along the Z-direction. The optical disc drive is further provided with means for generating a focus error signal which is representative for the

5   magnitude of a focus error. As is well-known to persons skilled in the art, such focus error signal can be derived from the optical read signal, so it is not necessary here to explain in great detail how a focus error signal is generated.

The controllable actuator is controlled by a controller which receives the focus error signal as an input signal, and which generates a drive signal for the actuator, the

10 actuator being responsive to this drive signal by displacing the objective lens. The whole setup is such that the focal error is reduced by the displacement of the objective lens. In other words, the controller is designed to generate an output drive signal such that its input error signal is reduced.

In the following, discussion will focus on the behavior of the controller. In

15 principle, any well-known type of device for generating an error signal may be used to generate the input signal for the controller and any type of well-known actuator may be used for obeying the commands of the drive signal outputted by the controller. The present invention relates specifically to the design of the controller, and to a method for generating an actuator drive signal in response to receiving an input error signal.

20   Figures 1A-B are graphs schematically illustrating possible characteristics of prior art controllers. The horizontal axis represents the magnitude of the input error signal FE. The vertical axis represents the output drive signal Sd. Figure 1A illustrates a linear characteristic: the drive signal Sd is directly proportional to the input error signal FE. A controller of this type is also indicated as "proportional controller". In this case, the control

25 characteristic of the controller is represented by a straight line 1, which makes an angle α with the horizontal axis, which angle indicates the gain of the controller. More particularly, if the gain G is defined by the following formula:

$$G = Sd/FE,$$

then the gain of the proportional controller equals $\tan(\alpha)$.

30   Briefly stated, a higher gain will result in a faster response of the controller, so the overall magnitude of the error signal FE will be smaller. In other words, the higher the gain, the smaller the error. However, it is not advisable to choose the gain G too high, because this may lead to instability of the control system.

Figure 1B illustrates a known non-linear controller. In this case, the control characteristic of the controller is described by two straight lines, a first line 2 crossing zero and making an angle α with the horizontal axis, this line extending between zero and a certain point P, corresponding with a certain threshold drive signal Sd_T and a certain threshold error

5   signal FE_T. Under normal circumstances, the error signal FE will be smaller than this threshold error signal FE_T, and the controller will behave according to this first straight line 2. However, under abnormal circumstances, for instance if the optical disc drive is subjected to a mechanical shock, the error signal may pass beyond said threshold level FE_T, in which case it is desirable to increase the corrective action of the controller by increasing the gain.

10 To this end, the characteristic comprises a second straight line 3, starting from said point P, and making an angle β with the horizontal axis larger than said angle α.

In theory, the non-linear characteristic of figure 1B is an improvement over the linear characteristic of figure 1A; in practice, however, such characteristic is not ideal because it appears to be very difficult to find a setting which is suitable in different situations.

15 It is possible to tune the non-linear controller to function well for one situation, but in another situation, where the noise content of the error signal is larger, the settings of the controller are not usable. A change in noise contribution can be caused by a change of disc. Of course, an optical disc drive should be able to handle a variety of optical discs in a reliable manner.

Therefore, an objective of the present invention is to provide an improved

20 controller with improved controller characteristic, capable of reducing errors for multiple optical discs without the necessity of adapting controller settings for each new optical disc.

In the prior art non-linear controller with the non-linear characteristic illustrated in figure 1B, the controller switches its gain between a low value (line 2) and a high value (line 3), the decision as to which gain to use depending on one parameter only,

25 this parameter being the error signal FE. If the input error signal FE is lower than said threshold level FE_T, the controller will select its lowest gain (line 2), whereas if the input error signal FE is above said threshold level FE_T, the controller will select its highest gain. In contrast, according to an important aspect of the present invention, the controller bases its decision regarding which gain to use on at least two input parameters.

30 These and other aspects, features and advantages of the present invention will be further explained by the following description with reference to the drawings, in which same reference numerals indicate same or similar parts, and in which:

figures 1A-B are graphs schematically illustrating characteristics of prior art controllers;

figure 2A is a functional block diagram schematically illustrating an embodiment of a controller according to the present invention;

5   figure 2B is a functional block diagram schematically illustrating a processor unit;

figure 3 is a graph illustrating the characteristic of an embodiment of the controller of figure 2A;

figures 4A-4C are graphs illustrating simulations;

10   figures 5A-5C are graphs illustrating simulations.

Figure 2A is a functional block diagram schematically illustrating a controller device 30, comprising a first controller unit 33, a second controller unit 34, a processor unit 35, and a controllable switch unit 40. The controller device 30 has a first input 31 for

15   receiving an input error signal ϵ, and an output 39 for providing a controller output signal Sd.

The first controller unit 33 has an input 33a coupled to said first controller input 31, and has an output 33c providing an output signal $S1(\epsilon)$. The first controller unit 33 may be implemented as a conventional controller. The first controller unit 33 may be a proportional controller having a characteristic such as illustrated in figure 1A. The first

20   controller unit 33 may also be a PI controller, in which case the output signal $S1(\epsilon)$ is generated on the basis of the input error signal ϵ, and signals obtained by integrating the input error signal ϵ one or more times, and/or signals obtained by integrating previous output signals (feedback) one or more times, as will be clear to a person skilled in the art. The first controller unit 33 may also be a PD controller, in which case the output signal $S1(\epsilon)$ is

25   generated on the basis of the input error signal ϵ and signals obtained by differentiating the input error signal ϵ and/or previous output signals one or more times, as will be clear to a person skilled in the art. The first controller unit 33 may also be a PID controller, in which case the output signal $S1(\epsilon)$ is generated on the basis of the input error signal ϵ, signals obtained by differentiating the input error signal ϵ and/or previous output signals one or more

30   times, and signals obtained by differentiating the input error signal ϵ and/or previous output signals one or more times, as will be clear to a person skilled in the art. Since PI controllers, PD controllers, and PID controllers are known per se, it is not necessary here to discuss their design and operation in great detail.

Similarly, the second controller unit 34 has an input 34a coupled to said first controller input 31, and has an output 34c providing an output signal $S2(\epsilon)$. As mentioned above with reference to the first controller unit 33, the second controller unit 34 may be implemented by a conventional P-controller, PI-controller, PD-controller, PID-controller.

5   The controllable switch unit 40 has a first input 43 coupled to the output 33c of the first controller unit 33, a second input 44 coupled to the output 34c of the second controller unit 34, and an output 46 coupled to the controller output 39. The controllable switch unit 40 has at least two operative states. In a first operative state, its output 46 is coupled to its first input 43, such that the controller output signal Sd at the controller output
10   39 corresponds to the output signal $S1(\epsilon)$ of the first controller unit 33. The controller 30 as a whole now has a controller characteristic corresponding to the characteristic of the first controller unit 33. This situation will be referred to as "the controller device 30 operates in a first operative mode".

        In a second operative state, the output 46 of the controllable switch unit 40 is
15   coupled to its second input 44, such that the controller output signal Sd at the controller output 39 corresponds to the output signal $S2(\epsilon)$ of the second controller unit 34. The controller 30 as a whole now has a controller characteristic corresponding to the characteristic of the second controller unit 34. This situation will be referred to as "the controller device 30 operates in a second operative mode".

20   For selecting its first or second operative state, the controllable switch unit 40 is responsive to a signal Sc received at a control input 45, which input is coupled to an output 35c of the processor unit 35. The processor unit 35 has an input 35a coupled to said first controller input 31 for receiving the input error signal ϵ. The processor unit 35 generates its output signal Sc on the basis of the input error signal ϵ and on the basis of at least one further
25   parameter ν, which indicates the changing rate of the error signal ϵ, as will be discussed below with reference to figure 2B, which is a functional block diagram of an embodiment of the processor unit 35.

        Figure 2B is a functional block diagram schematically illustrating an embodiment of the processor unit 35, having two inputs 35a, 35b and an output 35c. The first
30   input 35a is for receiving an input error signal ϵ. The processor unit 35 comprises an adder 73 having an input 73a receiving the error signal ϵ from the first input 35a.

        A signal representing the changing rate of the error signal ϵ, i.e. representing the velocity of the object concerned, will hereinafter be indicated by v. Such signal may be provided by an external detector, coupled with the object in question to detect its speed. In

principle, any suitable velocity detector may be used, so it is not necessary here to explain the design and functioning of a velocity detector. Suffice it to say that such velocity detector (not shown) is capable of providing a velocity signal v at a second input 35b of the processor unit 35.

5   However, it is also possible that the processor unit 35 itself is capable of deriving a velocity signal v from the input error signal ϵ by calculating the velocity v as the first time-derivative of the error signal ϵ, according to the following formula:

$$v = d\epsilon/dt$$

In the functional block diagram of figure 2B, the processor unit 35 is shown as

10   having a calculating unit 50 having an input 51 receiving the error signal ϵ, this calculating unit 50 being designed to provide at its output 52 the first time-derivative (d/dt) of its input signal. Since such calculating units are known per se, and a prior art calculating unit may be used here, it is not necessary here to discuss the design and operation of such calculating unit in great detail. However, it is noted that the calculating unit 50 may be implemented as a

15   hardware device, but may also be implemented in software.

The processor unit 35 may be specifically designed for receiving an input error signal ϵ as well as an input velocity signal v. In that case, the processor unit 35 will have two inputs 35a and 35b, and the calculating unit 50 may be omitted. On the other hand, it is also possible that the controller 30 is specifically designed to only receive an input error signal ϵ,

20   in which case the second input 32 may be omitted. In the preferred embodiment shown in figure 2B, the controller 30 is usable with or without an external velocity signal v, as desired. To this end, the processor unit 35 comprises a switch 60 having a first input 61 coupled to the output 52 of the calculating unit 50, and having a second input 62 coupled to the second input 35b of the processor unit 35. The switch 60 has an output 63, and is capable of connecting its

25   output 63 with either its first input 61 or its second input 62. In the case of operation in conjunction with a velocity detector, the switch 60 will be set in a position connecting the output 63 with its second input 62. In the case of operation without a velocity detector, the switch 60 will be set in a position connecting its output 63 to its first input 61. Thus, at the output 63 of the switch 60, the velocity signal v is always present.

30   It is noted that, in stead of receiving a velocity signal v, or calculating the velocity signal v by calculating the first time derivative of the error signal ϵ, it is also possible to use a state estimator, i.e. a filter estimating the value of a parameter (such as speed) from an estimate which is relatively inaccurate due to noise. Such estimators are known in the art,

therefore it is not necessary here to describe their design and functioning in great detail here. By way of suitable example, a Kalman state estimator is mentioned here.

The adder 73 has a second input 73b coupled to receive a signal derived from said velocity signal v. Figure 2B illustrates that the velocity signal v is processed before
5   being applied to the second input 73b of the adder 73. In the preferred embodiment illustrated in figure 2B, this pre-processing comprises the steps of squaring the velocity signal v by a square calculator 71, and multiplying the squared velocity signal v^2 with a constant value K by a multiplier 72, so that the adder 73 receives $K \cdot v^2$.

In the adder 73, this input signal $K \cdot v^2$ is added to the error signal ϵ received at
10 the first input 73a, to yield a summation Σ, which is provided to a first input 74a of a comparator 74. A second input 74b of the comparator 74 receives a signal indicating a transition level T_L. An output 74c of the comparator 74 is coupled to the output 35c of the processor unit 35. The comparator 74 compares the summation Σ received at its first input 74a with the transition level T_L. If the summation Σ is below this transition level T_L, the
15 comparator 74 provides an output signal Sc having a first value. Otherwise, if the summation Σ is above said transition level, the output signal Sc has a second value.

The switch 40 is responsive to said output signal Sc by selecting its first operative state if the control signal Sc has its first value, and by selecting its second operative state if the control signal Sc has its second value.
20 Alternatively, it is possible that the processor unit 35 provides the summation Σ as output signal Sc, and that the comparator 74 is incorporated in the switch 40.

The comparator 74 may have a characteristic with hysteresis, i.e. a higher transition level T_{L1} for rising summation Σ and a lower transition level T_{L2} for falling summation Σ, as will be clear to a person skilled in the art.
25 Since a square calculator, a multiplier, an adder, and a comparator are commonly known components, and such prior art components may be used in the controller 30 of the present invention, it is not necessary here to discuss the design and operation of such components in great detail. However, it is noted that such components may be implemented in hardware, but may also be implemented in software.
30 In a relatively simple embodiment, the first controller unit 33 is a proportional controller, having a characteristic as illustrated in figure 1A, while the second controller unit 34 outputs a constant output signal S2 irrespective of the error signal ϵ. The resulting characteristic of the controller device 30 is illustrated in figure 3, wherein the horizontal axis

represents the error signal ϵ and wherein the vertical axis represents the controller output signal Sd. Since the characteristic preferably, although not necessarily, is symmetrical with respect to the origin point (0,0), figure 3 only shows one quadrant of the characteristic. The inventive controller has two operative modes, and is switchable between these two operative modes on the basis of at least two parameters. In its first operative mode, when switch 40 is in its first operative state and the controller's behavior is determined by the first controller unit 33, the controller has a linear characteristic, illustrated by a straight line 11 in figure 3, this straight line 11 crossing the origin. In this first operative mode, the output drive signal Sd of the controller is linearly proportional to the error signal ϵ.

In its second operative mode, when switch 40 is in its second operative state and the controller's behavior is determined by the second controller unit 34, the output drive signal Sd is substantially constant, irrespective of the exact magnitude of the input error signal. This second mode, which will also be indicated as constant mode, is illustrated by a second straight line 12 in figure 3, this second straight line 12 being a horizontal line. The first line 11 and the second line 12 meet each other in a transition point 13; the error signal level corresponding to this transition point 13 will be referred to as normal transition threshold level T_N.

In figure 3, the level of the output drive signal in the constant mode is indicated as S_{max}, indicating the maximum output signal that this controller may provide. It is noted that this maximum level may be the upper limit of the capabilities of the second controller unit 34, i.e. the controller is simply not capable of generating any output signal having a magnitude larger than S_{max}. It may also be that this upper limit corresponds to a maximum level of a power amplifier driving the actuator. However, it may also be that this level S_{max} is defined by a software or hardware limiter, and that the level of S_{max} may be set by setting such limiter, either on manufacture of the controller or as a user setting.

Under normal circumstances, the controller device 30 behaves as an ordinary linear controller, operating in the first or linear operative mode. Under such normal circumstances, the input error signal ϵ is smaller than the normal transition level T_N, and the controller generates its output drive signal Sd in accordance with the characteristic of the first straight line 11. This will be expressed as the controller device 30 moving along the first line 11.

If the input error signal ϵ is slowly increased, the controller device 30 will travel the first straight line 11 until the transition point 13 is reached, upon which the

controller device 30 will make a transition to the second operative mode and travel the

second straight line 12, i.e. it will keep its output drive signal constant. It is noted that,

normally, in a prior art controller, such transition will also be made, i.e. if the input error

signal ϵ is so large that the controller reaches saturation.

5   The prior art controller discussed above with reference to figure 1B also has

two operative modes, each mode being characterized by a line portion in the characteristic

Sd/FE diagram. These two operative modes according to the prior art are defined exclusively

by the input signal FE: below a certain threshold level, the controller always is in its first

operative mode, and above this threshold level, the controller always is in its second

10   operative mode. In contrast, according to an important aspect of the important invention, the

two operative modes have a certain overlap, illustrated by a line portion 12a of the second

straight line 12, this line portion 12a extending beyond the transition point 13 to lower values

for the input error signal. This line portion 12a may have an end point indicated as lower

limit 14; the corresponding error signal level is indicated as lower limit threshold level T_{LL}.

15   This lower limit threshold level T_{LL} may be larger than zero, but preferably line portion 12a

extends all the way down to the vertical axis, i.e. the end point 14 may correspond to an input

error signal zero.

          Thus, in the input error range from T_{LL} to T_N, the controller device 30 has two

characteristics, and is switchable between these two characteristics, or, in other words, for a

20   certain input error signal in the range from T_{LL} to T_N, the controller may be in any of its two

operative modes, even for the same input error signal. Switching between these two operative

modes is done on the basis of the summation signal Σ, which contains a substantial

contribution of a second signal (ν), indicative of the rate at which the error signal ϵ changes,

as will be discussed below.

25   If the error signal ϵ is above the normal transition threshold level T_N, the

output signal Sd will always be generated in accordance with the second operative mode, i.e.

the constant mode (12).

          If the input error signal ϵ is below the normal transition threshold level T_N but

above the lower limit threshold level T_{LL}, while the changing rate is relatively small, then the

30   output signal S will be generated in accordance with the first operative mode (11). Otherwise,

if the input error signal ϵ is below the normal transition threshold level T_N but above the

lower limit threshold level T_{LL}, while the changing rate is relatively large, then the output signal S will be generated in accordance with the second mode, i.e. the constant mode (12a).

Finally, if the input error signal ϵ is below the lower limit threshold level T_{LL}, the output signal S will always be generated in accordance with the first operative mode, i.e.

5   the linear mode (11).

In the case of an optical drive, the error signal ϵ is in fact a measure for the position of an object (objective lens, or optical head); in that case, the changing rate of the error signal is in fact a measure for the actual velocity of this object with respect to a target object to be followed by said object, e.g. a track of the optical disc drive. Large velocities

10 will for instance occur in extreme circumstances like mechanical shock. For such extreme circumstances, it is desirable that the controller device 30 operates in the second operative mode, which gives the highest possible repressive force.

The transition level T_L and the multiplying constant K may be fixed values, defined on manufacture of the processing unit 35. It is, however, also possible that the

15 multiplier 72 is settable so that the multiplying constant may be varied by a user. The same applies to the comparator 74 in respect of the transition level T_L. Preferably, said multiplying constant K and said transition level T_L are chosen in conjunction with operative characteristics of the actuator for which the controller is intended. This will be explained as follows.

20   As mentioned before, the actuator receiving the drive output signal from the controller device 30 will exert a force on the object concerned (objective lens, optical head), such force resulting in an acceleration of this object. In principle, the force exerted will be higher if the drive signal Sd is larger, and hence the acceleration caused by this force is larger. However, the acceleration can not be infinitely high. In practice, the acceleration is

25 limited by a maximum acceleration level a_{max}.

Assume that, at a certain time τ, the error signal ϵ has a certain value $\epsilon(\tau)$, and that the velocity signal v has a certain value $v(\tau)$. These values correspond with a certain position of the object concerned (objective lens, optical head) deviating from a target position, and a velocity of this object, respectively. Assume further that the actuator exerts a

30 constant force F on this object, having a direction urging the object toward its target position with a constant acceleration a, i.e. having a direction reducing ϵ. Further, assume that the velocity v has a direction away from the target position, such that in the immediate future the acceleration a will reduce the velocity v but the error signal ϵ will increase. It can easily be

shown that, if the acceleration a is kept constant, the object will achieve a maximum

deviation from its target position, corresponding to a maximum error signal ϵ_{max}, in

accordance with the following formula

$$\epsilon_{max} = \epsilon(\tau) + v(\tau)^2/2a.$$

5   Obviously, the larger the velocity $v(\tau)$ is, the larger will be the maximum

deviation ϵ_{max}.

If the acceleration a is increased, this maximum deviation ϵ_{max} will decrease.

However, as stated above, the maximum acceleration in this system has an upper limit a_{max}.

Therefore, the maximum deviation ϵ_{max} can not be made smaller than a value $\epsilon_{max,min}$

10   according to the following formula

$$\epsilon_{max,min} = \epsilon(\tau) + v(\tau)^2/(2a_{max})$$

In the controller device 30, the constant K is selected to be at least

approximately equal to $1/(2a_{max})$. Then, the summation Σ is equal to the minimally

achievable value $\epsilon_{max,min}$ of the maximum deviation ϵ_{max}.

15   In the controller device 30, the threshold level T_L with which the summation Σ

is compared, now corresponds to a limit value of the acceptable deviation ϵ. As long as the

summation Σ stays below this acceptable limit T_L, it is predicted that the maximum deviation

ϵ_{max} will be within acceptable limits, and the controller device 30 is allowed to operate in its

linear mode (11). If, on the other hand, the summation Σ exceeds the acceptability level T_L, it

20   is predicted that the maximum deviation ϵ_{max} will appear to be a large value, larger than

acceptable, due to perhaps some unforseen external circumstances, and the controller device

30 decides to take emergency action by switching its operation to the second operative state

in which the corrective action of the actuator is as large as possible.

The performance of the controller proposed by the present invention was

25   investigated by running simulations. Figures 4A-4C illustrate the result of simulation where

an objective lens was assumed to oscillate, due to a mechanical shock, with a decreasing

amplitude about its target position, the deviation of the objective lens from this target

position being expressed as error ϵ (μm). In the simulation illustrated in figure 4A, the

controller device 30 was assumed to operate as a normal PID-controller, its gain having a

30   linear characteristic as illustrated in figure 1A. In other words, with reference to figure 2A,

the first controller unit 33 has a PID characteristic, and the switch 40 is constantly operated in its first operative state.

In the simulation illustrated in figure 4B, the controller was assumed to have a switching gain characteristic as illustrated in figure 1B, the linear characteristic portion (2)

5   corresponding to the linear characteristic (1) of the PID-controller of figure 4A. The transition point P corresponded to an error ϵ of 0.1 μm. The first gain $G1 = \tan(\alpha)$ of the linear characteristic portion (2) had a value $9 \cdot 10^4$; the second gain $G2 = \tan(\beta)$ of the second characteristic portion (3) had a value $59 \cdot 10^4$. In other words, with reference to figure 2A, the first controller unit 33 has a linear PID characteristic with a first gain $G1 = 9 \cdot 10^4$, and the

10 second controller unit 34 has a PID characteristic with a second gain $G2 = 59 \cdot 10^4$. In the processor unit 35, the constant K is zero, and the transition level T_L equals 0.1 μm.

Figure 4C illustrates the performance of a controller operated in accordance with the present invention. Again, the first controller unit 33 has a linear PID characteristic with a first gain $G1 = 9 \cdot 10^4$, and the second controller unit 34 outputs a constant output

15 signal, as discussed earlier with reference to the horizontal characteristic 12a of figure 3. The transition level T_L of the comparator 74 equals 0.1 μm for rising signals, and 0.09 μm for falling signals (hysteresis). The value of K was set to be equal to $1/(2a_{max})$, a_{max} being equal to 100 m/s^2.

By comparing figure 4C with figure 4B it clearly follows that the maximum

20 deviation occurring when using the controller proposed by the present invention is much smaller than the maximum deviation when using the controller illustrated in figure 4B.

Figures 5A-5C illustrate the results of simulation identical to the simulations of figures 4A-4C, with the additional feature that the system was now assumed to contain noise. It can clearly be seen in figure 5B that the switching gain controller having a

25 characteristic as illustrated in figure 1B, in the case of noise, may suffer from very strong oscillation peaks, such as for instance shown at 10 ms, at 38 ms and at 79 ms. It can clearly be seen from figure 5C that the oscillator proposed by the present invention is free from such strong oscillation peaks.

It should be clear to a person skilled in the art that the present invention is not

30 limited to the exemplary embodiments discussed above, but that various variations and modifications are possible within the protective scope of the invention as defined in the appending claims.

For instance, the characteristic of the controller is described as a combination of two straight lines 11 and 12, intersecting each other. However, the fact that the two lines are straight is not essential; those lines may be curved. Relevant is that the controller is capable of operating in at least two possible operative modes, each mode having a

5   corresponding characteristic, and that at least two of said characteristics have an overlap in a range of error signal values $[T_{LL}\text{-}T_N]$. Further it is relevant that the controller is capable of switching from one mode to another, based on the value of at least one other parameter, which preferably is the time-derivative of the error signal, so that the controller can be in any of its modes even when the error ϵ is the same.

10   In a preferred embodiment, one of the characteristics is a maximum characteristic, i.e. a horizontal line (12), while another one of the characteristics is a lower line (curved or straight) intersecting the origin and intersecting the maximum characteristic (12). In a further elaboration, the controller may have a third characteristic or intermediate characteristic between the above-mentioned lower and maximum characteristics. If the

15   velocity v is relatively low, the controller follows the lower characteristic; if the velocity v is relatively high, the controller follows the maximum characteristic; if the velocity v is within an intermediate range, the controller follows the intermediate characteristic.

          Further, in the above-described examples, a criterion Σ is defined on the basis of two parameters ϵ and ν. It is, however, also possible to define a criterion on the basis of

20   three or more parameters. For instance, as a third parameter, the second derivative $d^2\epsilon/d\epsilon^2$ may be used. In any case, if the number of parameters equals n, together they define the coordinate system of an n-dimensional space, and the criterion divides this n-dimensional space in two sections. The controller device is operated in one mode if its state, as projected on said coordinate system, corresponds to a point in one section of said n-dimensional space,

25   whereas the controller device is operated in another mode if its state corresponds to a point in another section of said n-dimensional space. In order to provide a behavior with hysteresis, two parallel criterions Σ^+ and Σ^- may be defined, differing only slightly, so that, when the controller's state travels from said one section to said other section of said n-dimensional space, it will cross the two parallel criterion boundaries consecutively, and the controller will

30   change its mode only on the second boundary crossing.